Exploring the Effect of Technological Diffusion on Energy Transition: A Path to Low Carbon Economy and Sustainability

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Abstract

Transition towards renewable and low-carbon energy is now the core objective of energy policy of all countries striving to achieve sustainable development goals. This necessitates the understanding of accelerating factors of energy transition. Therefore, this study investigated the influence of technological diffusion on energy transition using data from South Asia and G20 countries from 2000 to 2022. The data estimation starts with cross-sectional dependence and unit root test, and both these tests suggest the use of the feasible generalized least square method as the primary estimation technique. The feasible generalized least square findings show that technological diffusion has a positive and significant effect on energy transition in South Asia and G20 countries. The results also demonstrate that the effect of technological diffusion on energy transition is stronger in G20 countries than in South Asia. Findings further show that globalization and governance accelerate energy transition, but the effect of governance on energy transition in South Asia is statistically insignificant. In contrast, Income per capita has an inverted U-shaped relationship with energy transition in both countries. Finally, this study makes some recommendations for further enhancing energy transition in light of the findings of this study.

Keywords: Energy Transition, Technological Diffusion, FGLS, South Asia, G20.

Introduction

The last three decades have seen a rapid rise in energy consumption and economic expansion, which is the primary cause of the increasing environmental degradation that continues to endanger human health and the environment (Agbede et al., 2021). Energy consumption, along with economic growth, is considered the leading reason for environmental pollution as WHO (2018) highlighted that primary energy consumption is responsible for more than 85 per cent of CO_2 emissions, and thus, this excessive emission of CO_2 led to the life of about seven million people to the death and caused harms to animal species. The study of Usman et al. (2019) also supports the harmful effect of energy consumption on the environment as their findings demonstrate that an increase in energy consumption in the early stage of development causes an increase in the emission of CO_2. The study of Usman et al. (2022) shows that a one per cent increase in

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nonrenewable energy consumption causes an increase in CO2 emission by 0.71 per cent, thus supporting the claim that energy consumption negatively affects the environment. It is evidenced by extant literature that the extensive use of nonrenewable fossil fuels contributes significantly to environmental degradation by releasing excessive amounts of greenhouse gases (Kuşkaya & Bilgili, 2020).

Renewable energy sources are considered environmentally friendly and emit less CO2. As to REN21, renewable energy produces little or no greenhouse gas emissions, less or no air pollution, is inexpensive to avail, provides employment, and is available to everyone. The study by Scandrett (2017) highlighted that electricity generated from renewable energy sources emits 90 to 99 % less greenhouse gas than electricity generated from coal-fired power plants. Renewable energy is an environmentally preferable form of energy to fossil fuels as fossil fuels release pollutants when burnt. Naimoglu (2023) postulates that the global economy, particularly those of developing nations that depend on imported energy, would benefit more from using renewable energy. Renewable energy sources help developing countries achieve energy security and meet their present and future energy needs without generating secondary waste (Owusu & Asumadu-Sarkodie, 2016). Thus, using renewable energy to mitigate environmental pollution has been considered an effective strategy.

Due to the environmental consequences of nonrenewable energy (fossil fuels) consumption and the environmentally friendly effects of renewable energy consumption, governments of different countries and international agencies have started making efforts for energy transition. Energy transition is the process of the energy industry switching to a low-carbon model. It is a global challenge that involves significant technological and economic changes in energy production, supply, and consumption to reduce the energy industry's environmental effects (Gitelman, 2023). The switch to renewable energy sources from fossil fuels is a crucial component of the energy transition, and the transition to renewable energy is at the heart of energy policies in many countries (Berkhout, 2012). Sustainable Development Goal 7 also emphasizes energy transition, and this goal's focus is access to affordable, modern, and sustainable energy sources (Ibrahim, 2023).

Energy transition makes the trajectory of sustainable development, as Noor et al. (2024) state, and the transition to renewable and low-carbon energy sources is necessary for achieving sustainable development. Sustainable Development Goal 7 also advocates the replacement of traditional energy sources with sustainable, affordable and reliable energy sources (Chen et al., 2023). Transition to renewable energy facilitates different facets of sustainable development. Renewable energy significantly reduces the emission of greenhouse gases, protects and preserves the natural environment and thereby helps achieve environmental sustainability (Noor et al., 2024). Energy transition causes a reduction in energy poverty (Zhao et al., 2022), leading to a decline in income inequality (Nguyen & Nasir, 2021). Energy transition also helps improve public health, an essential facet of sustainable development, through its effects on energy poverty (Pan et al., 2021). Sustainable Development Goal 7 (emphasizing energy transition) is directly connected with Sustainable Development Goal 13, which emphasizes taking action to mitigate climate change (Elavarasan et al., 2023). Therefore, energy transition is a significant path to sustainable development (Shyu, 2021).

Technological innovation is considered a key means of attaining objectives of energy policies, such as enhancing accessibility to clean energy and decreasing air pollution and has also been widely recognized as a key determinant of climate change mitigation (Fernandez et al., 2022). Khan et al. (2022) state that technological innovations provide a technical base for increasing renewable energy consumption. Renewable energy technologies enhance energy plants' efficiency and constantly ensure output (Park, 2005). Recently, a growth in renewable energy technologies has been noticed. This growing trend in renewable energy technologies, particularly environment-related technologies, will lead the energy sector to an energy mix with a higher share of renewable energy and, thus, transit the global energy system towards a more sustainable energy system (Geng & Ji, 2016). However, technological innovations need to be diffused to get the benefits for which these technologies are designed, and these technologies do not produce economic outcomes unless these technologies get diffused (Mukoyama, 2003). Adaptation of technological innovations can increase renewable energy consumption. Thus, these innovations will help meet energy demand (Khan & Su, 2022). Therefore, this study evaluates the effect of technological diffusion on energy transition in South Asia and G20 countries, as technological diffusion is considered an essential determinant of energy transition.

The study on the determinants of energy transition in South Asia and G20 countries holds paramount significance in the contemporary global context. Cerutti et al. (2021) postulate that South Asia is the most prone region to adverse climate events and is the largest emitter of greenhouse gases. A report by Shrestha et al. (2012) states that South Asia will be a carbon-intense region from 2005 to 2030 if renewable energy technologies are not deployed and climate change policies are not executed. In the coming decades, the energy consumption of South Asian countries is projected to increase substantially. Canton (2021) states that the energy demand in South Asia will rise by 2.3 per cent per year from 2020 to 2040. Citarist (2022) projected that India's energy demand will account for nearly 25 per cent of global energy demand in 2040. This substantial increase in energy demand will cause severe environmental consequences for the whole region.

On the other hand, South Asia has plenty of opportunities to produce and generate renewable energy, such as solar energy. IRENA (2020) projected that South Asia can generate over forty thousand gigawatts of solar energy. G20 countries also meet most of their energy demand using fossil fuels such as gas, coal, and oil (Asante et al., 2022). From 2000 to 2021, the fossil fuel consumption of G20 countries increased by 45 per cent (Li et al., 2022). The energy demand by G20 countries is expected to rise nearly 1.2 per cent between 2020 to 2024, which leads to a 19 per cent increase in their energy demand in the coming two decades. G20 countries also have the potential to meet their energy demand by up to 40-45 per cent through renewable energy sources (Irena, 2020). The heavy reliance of these countries on energy generated from fossil fuels can aggravate energy security issues and cause a shortage of fuels, along with detrimental environmental effects (Asante et al., 2022). These Challenges created for the world by excessive use of fossil fuels and, consequently, disastrous climate change have made the transition towards sustainable energy sources imperative.

The innovation diffusion theory explains the nexus of energy transition with technological diffusion. This theory postulates that diffusion of innovation depends on the relative importance of innovations, compatibility of innovations with society's goals and benefits gained from innovations. All these are the crucial drivers of energy transition (Rogers et al., 2014). Therefore, exploring the effect of technological diffusion on energy transition in these two regions becomes vital. Considering the dire need for energy transition, this study will make two significant contributions to accelerating the process. First, this study will explore the effect of technological diffusion on energy transition in South Asia and G20 countries, which will help the policymakers of these countries to design effective policies for energy transition. Second, this study will compare factors accelerating the energy transition in these two blocks and enable policymakers to gain insights from each other's experiences.

The second section of this study proceeds by conducting and presenting literature reviews of extant studies. The third section delineates the methodology employed in this study. The fourth section presents this study's results and thoroughly discusses them. Finally, the fifth section presents suggestions for policymakers and future research directions.

Literature Review

A growing body of research investigated factors influencing renewable energy consumption and energy transition, but we present in this section reviews of extant studies related to the effects of technological diffusion and control variables on renewable energy consumption.

Li et al. (2023) examined the impact of technical innovation on renewable energy using data from G10 countries. Research and development expenditures were used as a proxy for technological innovation, whereas renewable energy production measured in tons of oil equivalent was used to indicate energy transition. Their finding shows that the effect of technological innovation on renewable energy is more potent when its value is above the threshold level than the effect of technological innovation on renewable energy when its level is below the threshold level. Li et al. (2020) used data from OECD economies from 1990 to 2017 and examined the effect of technological innovation on renewable energy consumption. They also used research and development expenditure as an indicator of technological innovations. Their findings show the positive impact of technological innovation on renewable energy consumption. Zheng et al. (2021) used the number of patents to indicate technological innovation and investigated the nexus between renewable energy generation and technological innovation. They found a positive influence of technological innovations on renewable energy generation. Geng and Ji (2016) also used several patents as indicators of technological innovation and investigated the impact of technological innovation on renewable energy consumption in six major developed countries. The result shows a positive effect of technological innovation on renewable energy consumption.

The Environmental Kuznet Curve (EKC) hypothesis inferred the theoretical link between energy transition and income per capita. EKC postulates that at the early development stage, an income expansion causes environmental degradation due to a surge in unsustainable production and consumption patterns and disregard for the environment. After a threshold level of development, a further increase in Income causes a switch towards consumption and production of environmentally friendly and sustainable products, leading to environmental improvement (Taguchi, 2023; Rasheed et al., 2023). A rise in Income at an early stage of development increases the consumption of energy derived from fossil fuels, decreasing the share of renewable energy consumption in the overall energy mix. Thus, higher Income obstructs energy transition. After a point of a certain threshold level of Income, countries start increasing the consumption of renewable energy, improving the efficiency of energy use. Thus, the relationship between energy transition and Income per capita is positive (Ergun and Rivas., 2023). Greenwood et al. (2021) state that healthy growth, at the second stage of development, provides financial impetus for investment in renewable and environmentally friendly technologies that accelerate energy transition. Ergun and Rivas (2023) used the EKC hypothesis to evaluate the relationship between energy transition and Income. Their empirical findings demonstrate that the energy transition and income nexus align with the EKC hypothesis. Ballesta et al. (2022) empirically inspected the nexus between Income per capita and renewable energy consumption using data from European Union countries, and their study reveals the negative relationship between Income per capita and renewable energy consumption. Nguyen and Kakinaka (2019) examined the nexus between energy transition and income using data from low, middle, and high-income countries and found positive effects of Income on renewable energy consumption in middle-income and high-income countries and a negative relation between these two variables in low-income countries. Damette and Marques (2019) empirically examined the drivers of renewable energy consumption, including GDP, using data from 24 European countries, and their study's outcome shows the positive effect of Income on renewable energy transition. Damette and Marques (2019) further highlighted that high Income switches investors' preferences towards the development of renewable energy infrastructure, and thus, high Income leads to an increase in renewable energy deployment. However, this shift is restricted to high-income countries due to the cost-effectiveness of renewable energy deployment and high financial requirements for the energy transition. Taghizadeh-Hesary and Rasoulinezhad (2020) examined the nexus between economic growth and energy transition using the data from 54 Asia countries and divided the sample into three income groups, i.e., lower Income, middle-income and high-income countries, and their findings showed a positive effect of Income on energy transition in all three income groups.

The pollution halo hypothesis corroborates the nexus between globalization and the renewable energy transition. This hypothesis states that environmentally friendly technology, including renewable energy technologies and better management practices, get transferred from one country to another country through the international flow of investment and trade, and the flow of investment and global trade are parts of globalization (Nyeadi, 2023; ÖZTÜRK & ÖZ, 2016). Therefore, globalization is hypothesized to be a boosting factor in renewable energy consumption. Many empirical studies proved a positive relationship between globalization and renewable energy consumption. Zhang et al. (2022) examined the relationship of renewable energy development with globalization using data from countries of different income groups, and renewable energy consumption as a portion of total energy consumption was used as an indicator of renewable energy development. The findings show that globalization significantly expands the share of renewable energy consumption in the overall energy mix in three groups, i.e., higher-income, upper-middle-income, and low-income countries but does not expand renewable energy consumption in lower-middle-income countries. Gozgor et al. (2020) examined the effects of economic globalization on renewable energy consumption using data from 30 OECD countries and found the accelerating impact of globalization on renewable energy consumption. Mingxing et al. (2023) used the data of China from 1970 to 2016 to investigate the nexus between globalization and renewable energy consumption. They found the positive effect of globalization on renewable energy consumption. Salman et al. (2022) inspected the relationship between renewable energy consumption and globalization using data from high-income, upper-middle Income and lower-income countries. They found positive effects of economic and social globalization and negative impact of political globalization on renewable energy transition.

Xu et al. (2023) studied the effect of governance on green energy transition using data from ninety-one middle-income countries from 2000 to 2020. They found a positive relationship between governance and green energy transition. Hao (2023) inspected the role of governance in energy transition using the data of BRICS countries and found a positive influence of governance on energy transition both in the short run and in the long run.

The above-reviewed empirical studies demonstrate that most previous studies investigated the effect of technological innovations on renewable energy consumption. These studies used several patents and research and development expenditures as indicators of technological innovation. Patents are an output measure, and research and development expenditures are input indicators of technological innovations (Keller, 2004). Technological innovations do not create an immediate economic impact, and it takes time to achieve the desired changes. (Mukoyama, 2003). Any technological innovation creates little social and economic effects unless it gets diffusion. Hall (2004) defined technological diffusion as a process by which firms and consumers in the economy or society adopt new technology or replace old technology with the latest technology. Keeping in view the significance of technological diffusion for energy transition and the distinction between technological innovation and technological diffusion, this study attempted to explore the effect of technological diffusion on energy transition. The review of extant studies demonstrates that most of these studies examined the impact of several factors on renewable energy without any consideration of total energy consumption, which may not accurately show the diversion of preferences towards renewable energy as consumption of fossil fuel can grow at the same pace. This study used the percentage of renewable energy consumption in the overall energy mix, which better indicates the transition of energy from nonrenewable to renewable energy.

Research Methodology

To achieve the objective of this study, balanced panel data from 2001 to 2022 was used to investigate the effect of technological diffusion on energy transition in the two blocks of countries and to do a comparative analysis of energy transition in these two blocks. The dependent variable of this study is energy transition. The term "energy transition" describes the transformation of the global energy industry away from fossil-based energy production and consumption methods, such as oil, natural gas, and coal, toward lithium-ion batteries, wind, and solar energy (Guilbert & Vitale, 2021). The Independent variable of this study is technological diffusion measured by the human capital index. Human capital determines the absorptive capacity of technological innovations in a country. A country must have a skill or knowledge for the successful adoption of new technologies, and this knowledge and skills can be available in the form of human capital (Keller, 2004). Therefore, human capital was used as a measure of technological diffusion. Control variables are globalization measured by the globalization index. Following Simionescu et al. (2021), governance was measured by the institutional quality index. Per capita Income was measured by GDP per capita at constant 2015 US dollars, and the square of GDP per capita was also added as a regressor to check the inverted U-shaped relation of Income per capita with energy transition. The data of all variables employed in this study was taken from the World Penn Table (2023), World Bank (2023), KOF (2023) and Fraser Institute (2023). Table 1 presents the variables' names, data sources, and measures.

Table 1: Description of the data series

Variables	Abbreviations	Unit	Data Source
Energy Transition	ET	Renewable energy as a percentage of total energy use	World bank (2023)
Technological Diffusion	TD	Human capital Index	World Penn Table (2023)
Globalization Index	GI	Index	KOF (2023)
Governance	GOV	Index	Fraser Institute (2023)
Income Per Capita	IPC	GDP Per Capita Measured at constant 2015 US Dollar	World Bank (2023)

Equation 1 was set up to achieve the objective of this study i.e., to empirically examine the effect of technological diffusion on energy transition. The equation was estimated separately for both sets of countries.

$$lnET_{it} = \beta_0 + \beta_{5it}lnTD_{it} + \beta_{1it}lnIPC_{it} + \beta_{2it}lnIPCS_{it} + \beta_{3it}lnGI_{it} + \beta_{4it}lnGOV_{it} + \varepsilon_{it} \quad (1)$$

Where ET is energy transition. TB is a technological diffusion. IPC is Income Per capita. IPCS is the square of income per capita. GI is globalization index. GOV is governance index. Ln shows that all variables were converted to natural log. βs, ε, i and t denotes estimated parameters, error terms, observations, and time respectively.

This study proceeds through few steps. The first step is to perform pre-estimation tests i.e., cross-sectional dependence test and inspecting stationarity of variables/series. Economic time series often exhibit trends which cause variation in mean, variance, and covariance of time series over time and thus, these series turn out to be non-stationary (Ryan et al., 2023). Econometrics literature emphasizes the incorporation of stationary series, i.e., series having constant mean, variance, and covariance, in regression model for parameters estimation and hypothesis testing. Incorporating non-stationary series leads to spurious regression which shows misleading results i.e. rejection of true null hypothesis (Giles,2007). Therefore, it is imperative to examine each series of the model for non-stationarity problem. Often, researchers use first generation panel unit root test to examine the stationarity of series in case of panel data. These first-generation panel unit root tests assume cross-sectional independence. i.e., cross-sectional units are uncorrelated but in reality, cross-sectional units are correlated and interdependent due to unobserved common factors and violate the basic assumption of first-generation unit root tests. The reason behind the cross-sectional dependency is the increasing globalization i.e. growing financial and economic integration among countries in recent decades, use of same technology by firms and likelihood of same response of individuals to a common shock (Pesaran, 2021; Rasheed et al., 2022). Therefore, the Pesaran cross-sectional dependence test, specified in equation 2, was used to examine the cross-sectional dependence in all series of this study.

$$CD = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \quad (2)$$

The result of CD test indicates the presence of Cross-sectional dependence, therefore, the CIPS, second generation unit root test specified in equation 2, was used to inspect the non-stationarity problem / unit root in all series.

$$CIPS(N,T) = \bar{T} = N^{-1}\sum_{i=1}^{N}(N,T) \quad (3)$$

The presence of Cross-sectional dependence in residuals does not make traditional fixed effect and random effect estimators inconsistent but these estimators become inefficient and produce biased standard errors. Fixed effect and random effect estimators become both inconsistent and inefficient when an unobserved factor, which creates interdependency in cross-sectional units, is also correlated with independent variables (De Hoyos & Sarafidis, 2006).

The second step is to examine the long run relationship between variables using three tests of cointegration i.e., Padroni, Kao and Fisher as economists are interested in long run relationship of variables (Asteriou & Hall, 2007). The null hypothesis postulates that all variables are not cointegrated whereas alternative hypothesis postulates that all variables are cointegrated. Padroni cointegration tests uses four statistics and at least four statistics must be significance for rejection of null hypothesis (Neal, 2014; Padroni, 1999). The Kao test uses Augmented Dicky Fuller (ADF) statistics and the probability value of ADF test must be significance for rejection of null hypothesis of no cointegration (Kao, 1999). The Fisher test uses trace statistics and maximum eigen values to check the cointegration of variables. The Fisher test indicates long run relationship between variables (cointegration) when null hypothesis of no cointegrating equation is rejected in Favor of at least one cointegrating equation (Maddala & Wu, 1999).

Finally, FGLS was used to estimate the model specified in equation 1 separately for both blocks of countries. Feasible generalized least square (FGLS) can estimate and model cross-sectional dependence, can produce both efficient and consistent standard parameters, and estimates cluster robust standard errors. FGLS can also produce efficient and consistent estimates in presence of serial correlation and heteroskedasticity (Bai et al, 2021). This study's variables face the problem of cross-sectional dependence, therefore, FGLS was used to estimate the model specified in equation 1.

Results and Discussion

The empirical investigation of this study begins with the descriptive statistics of variables employed in this study. Table 2 presents mean, standard deviation, minimum and maximum values of each variable for both blocks of countries. The mean of energy transition is 14. 04 percent whereas the mean value of energy transition is 52.71. The low mean value of energy transition is due to the higher demand of total energy demand by G20 countries and their energy demand accounts for more than eighty percent of world energy demand. These countries consume seventy percent of their oil and gas resources and ninety five percent of their coal resources (Kumari et al., 2021). As energy transition was measured as renewable energy consumption a percentage of total energy and these countries have less share of renewable energy in total energy due to high reliance of G20 countries on fossil fuel-based energy. The high mean of energy transition in South Asian countries is due to high renewable energy consumption by Nepal i.e. 84.37 percent during the sample period of this study and its most recent value of renewable energy, reported by World Bank, is 74.54 percent. The total energy demand of South Asian countries is also less than the G20 countries. G20 countries have higher income per capita than the South Asian countries. IPC of G20 countries is 23448.326 USD whereas the IPC of South Asian countries is 1555.318 USD during the sample period of this study. The mean value of globalization index in G20 countries is 72.67 which is higher than the mean value of globalization index of South Asian countries. The mean values of governance index and technological diffusion are higher in G20 countries than the mean values of these two variables in South Asian countries which implies that G20 countries have better governance and have more adaptation of renewable energy technologies than the South Asian countries.

Table 2: Descriptive Statistics

G20 Countries					
Variable	Obs	Mean	Std. Dev.	Min	Max
ET	418	14.04	12.451	.01	52.52
IPC	418	23448.326	17629.865	777.734	61829.844
GI	418	72.672	9.719	49	90
Gov	418	7.166	.892	4.72	8.76
TD	418	3.4	1.961	.014	13.382
South Asian Countries					
ET	110	52.71	18.299	25.79	91.31
IPC	110	1555.318	1024.687	556.368	4495.71
GI	110	51.805	7.346	33	63
Gov	110	6.163	.301	5.29	6.74
TD	110	2.021	.467	1.08	2.9

Pesaran cross-sectional dependence (CD) test was conducted to evaluate the basic assumption of first-generation unit test. The result of CD test, presented in table 3, shows that the null hypothesis of cross-sectional independence is rejected in favor of alternative hypothesis of cross-sectional dependence in case of both set of countries and concluded that there is cross-sectional dependence in both dependent and independent variables.

Table 3: Pesaran Cross-sectional Dependence test

	South Asia countries		G20 countries	
Variable	CD-test	p-value	CD-test	p-value
lnET	9.250***	< 0.01	2.230**	< 0.05
lnIPC	11.230***	< 0.01	27.420***	< 0.01
lngi	9.230***	< 0.01	39.830***	< 0.01
lnGov	4.010***	< 0.01	3.130***	< 0.01
lnTD	0.850	0.398	38.520***	< 0.01

Note: *** & ** represent significance at 1 and 5 percent levels of significance.

As the CD test result demonstrates the presence of cross-sectional dependence, therefore, CIPS second generation panel root unit test was used to examine the stationarity of series. CIPS was conducted with three specifications i.e. none, constant and constant and trend separately for both blocks of countries. The result, presented in table 4, indicates that all variables of this study are stationary with all three specifications except energy transition which is stationary at level with only one specification i.e., constant at 10 percent level of significance whereas with other two specifications, energy transition is stationary at first difference. Therefore, it is concluded that all variables are cointegrated.

Table 4: Unit Root Test

CIPS unit root test results for South Asia Countries						
Level				1st Difference		
Variables	None	Constant	Constant & trend	None	Constant	Constant & trend
lnET	-1.50	-2.66*	-2.87	-4.65***	-4.87***	-4.89***
lnIPC	-1.08	-1.51	-0.42	-5.29**	-5.47***	-5.45***
lnGI	-1.74	-2.50	-1.71	-3.07***	-3.30***	-3.18***
LnGov	-2.161	-2.319	2.41	-5.01***	-4.97***	-5.17***
lnTD	-0.98	-2.38	-1.81	-3.58***	-3.66***	-3.85***
CIPS unit root test Results for G20 Countries						
	Level			1st Difference		
Variables	None	Constant	Constant & trend	None	Constant	Constant & trend
LnET	-1.53	-1.97	-1.71	-2.52***	-2.84***	-3.32***
lnIPC	-0.79	-1.02	-1.45	-3.12***	-3.63***	-3.86***
LnGI	-1.55	-2.42	-2.51	-2.13***	-2.59***	-2.73**
lnGov	-1.582	-1.91	-2.10	-3.79***	-4.07***	-4.14***
lnTD	-1.41	-1.82	-1.81	-2.65***	-2.74***	-3.04***

Note: *** denotes significance at 1 percent level of significance.

As the result of CIPS test demonstrates that all variables become stationary at first difference and are cointegrated, therefore, three cointegration tests were used to examine the long run relationship between variables. Table 5 and 6 present the results of these three cointegration tests for both sets of countries. in case of G20 countries, four test statistics of Padroni test i.e., Panel PP-Statistic, Panel ADF-Statistic, Group PP-Statistic and Group ADF-Statistic are significant at one percent level of significance and thus, reject the null hypothesis of no cointegration in favor of cointegration among variables. The Padroni test also demonstrates the existence of long run relation among variables in case of South Asia as four statistics i.e. Panel v-Statistic, Panel ADF-Statistic, Group PP-Statistic and Group ADF-Statistic are significant. Three statistics, except Group PP-Statistic, are significant at one percent level of significance whereas Group PP-Statistic is significant at five percent level of significance.

Fisher cointegration test result demonstrates the existence of at least five cointegrating equations in the case of both sets of countries. Five cointegrating equations imply that all five independent variables have long run relationship with energy transition. This study can have up to five cointegrating equations as it has five regressors including square of GDP per capita (Income per capita). In the case of both blocks of countries, the probability values of trace statistic and Maximum eigen value are less than 0.01 for all five null hypotheses. The Kao cointegration test also rejects the null hypothesis that there is no cointegration among variables in favor of alternative hypothesis of existence of cointegration among variables. ADF test rejects null hypothesis of no cointegration at one percent level of significance and at five percent level of significance in cases of G20 countries and South Asia respectively.

Table 5: Panel Cointegration Tests (G20 Countries)

Padroni Cointegration Test				
Within dimension				
Test Statistics		Statistic	Prob.	
Panel v-Statistic		0.253536	0.3999	
Panel rho-Statistic		1.356235	0.9125	
Panel PP-Statistic		-10.68716	<0.01***	
Panel ADF-Statistic		-9.917730	<0.01***	
Between Dimension				
		Statistic	Prob.	
Group rho-Statistic		0.232300	0.59	
Group PP-Statistic		-2.829195	<0.01***	
Group ADF-Statistic		-2.817740	<0.01***	
Johansen Fisher Panel Cointegration Test				
Series: LNRE LNHC LNGOV LNGDP LNGI LNGDPS				
Hypothesized	Fisher Stat.*		Fisher Stat.*	
No. of CE(s)	(from trace test)	Prob.	(from max-eigen test)	Prob.
None	1042.	<0.01	502.4***	<0.01
At most 1	810.7	<0.01	466.3***	<0.01
At most 2	536.2	<0.01	323.2***	<0.01
At most 3	285.1	<0.01	182.4***	<0.01
At most 4	153.3	<0.01	119.0***	<0.01
At most 5	97.86	<0.01	97.86***	<0.01
Kao Cointegration Test				
Test Statistics	Coefficients	Prob. Value		
Augmented Dickey-Fuller	3.8609	<0.01***		

Note: ***denotes significance at 1 percent.

Table 7 presents the result from estimating equation 1 for both blocks of countries using FGLS. The result shows, at one percent level of statistical significance, the positive effect of technological diffusion on energy transition in both blocks of the countries G20 and South Asia countries. The coefficient of technological diffusion in G20 countries is greater than the coefficient of technological diffusion in South Asia Countries indicating stronger effect of technological diffusion on energy transition in G20 countries than the South Asian countries. Technological diffusion enhances energy transition by facilitating the widespread adaptation of renewable energy technologies, reducing cost, increasing efficiency gains and accessibility. (Sagar & van der Zwaan, 2006; Geels, 2004). This finding is supported by the findings of Khan and Su who investigated the effect of technological innovation on energy transition.

The coefficients of income per capita (IPC) are negative and are significant at 1 percent level of significance in both blocks whereas the coefficients of income per capita square (IPCS) are positive and significant at 1 percent level of significance in G20 countries whereas in case of south Asia, IPCS is significant at 5 percent level of significance. G20 countries have higher coefficients of both IPC and IPCS than South Asia countries which implies that the impact of income on energy transition is stronger in G20 countries than the impact of income on energy transition in South Asia. The negative coefficient of IPC and positive coefficient of IPCS are supported by EKC which states that as a country starts growing at its initial stage of development, its environment gets degraded due to increase in consumption and production of goods that are not sustainable, and consumption of such goods causes environmental degradation and after attaining a threshold level of growth, further increase in income diverts consumption and production of that country towards sustainable and environmentally friendly products (Grossman and Krueger, 1991; Rasheed et al, 2023). This theory supports the inverted U-shaped relationship between energy transition and income growth. Initial stage of income growth increases reliance on non-renewable (unsustainable) energy as people have more concern about their basic needs and they do not allocate more income to consumption of renewable energy due to high initial cost of renewable energy and low affordability to purchase renewable energy technologies. After threshold level of income, increase in income leads to more consumption of renewable energy consumption as the country has more income and thus, can afford renewable energy. Therefore, increase in income, after a threshold level of income, lead to a more environmentally sustainable energy mix (Ergun & Rivas, 2023). The empirical findings of Ergun and Rivas (2023) also corroborate this result.

The coefficients of globalization are positive in the case of both blocks of countries, but the coefficient is insignificant in south Asia whereas it is significant at 1 percent level of significance in G20 countries. The higher coefficient of globalization in G20 than South Asia and insignificant coefficient of globalization in South Asian countries imply that globalization contributes more towards energy transition in G20 countries than the South Asian Countries. The positive effect of globalization on energy transition is justified by Pollution Halo Hypothesis which states that globalization boosts energy transition by promoting cooperation among countries, increasing cross-countries investment in renewable energy technologies and dissemination of knowledge among countries (Bakhsh et al., 2017; Rasheed et al., 2023). Increasing globalization also reflects an increase in the volume of international trade and foreign direct investment inflows which bring in the technology related to renewable energy; therefore, globalization exerts positive effect on energy transition (Gozgor et al., 2020). The positive effect of globalization on energy transition found by this study is corroborated by the empirical findings of Padhan et al. (2020).

Table 7 further shows that, at one percent level of significance, the coefficient of governance is positive in the case of both sets of countries. The positive coefficients indicate the positive influence of improvement in governance on energy transition. The governance's coefficient of G20 countries is greater than the governance's coefficient of South Asia countries which implies that Governance of G20 countries has stronger effect on their energy transition than the governance of South Asian countries on their energy transition. This finding is corroborated by the findings of Yu and Guo (2023) who investigated the influence of governance on green energy transition in China. The likely reason of positive effect of governance on energy transition is the provision of conducive environment for installation of renewable energy technologies, encouraging innovation for enhancement of energy transition and can attract foreign investment for promotion of renewable energy (Wang et al., 2022). Theory of "Race to the top" also supports the positive influence of governance on energy transition as the countries under studies have formulated polices for energy transition, and use of renewable energy and effective governance can implement these polices effectively (Wang & Huang, 2021).

Table 7: FGLS Results for South Asia and G20 countries

G20 countries				South Asia countries		
Variables	Coefficients	Std.error	Prob:value	Coefficients	Std.error	Prob: Value
Constant	20.04 ***	0.10	< 0.01	-10.34***	3.14	<0.01
LnIPC	-5.40***	0.05	<0.01	-2.51**	0.089	<0.01
LnIPCS	0.31***	0.001	<0.01	0.20**	0.06	<0.01
LnGI	9.54***	0.03	<0.01	0.38	0.27	0.157
LnGov	2.71***	0.04	<0.01	2.36***	0.40	<0.01
LnTD	1.04***	0.01	<0.01	0.91***	0.26	<0.01

Note: **** and ** Show level of significance at 1 and 5 percent.

Conclusion and Recommendations

Keeping in view the struggle for restricting world temperature below 1.5 degree and attainment of sustainable development goals by all stakeholders, this study attempted to investigate the effect of technological diffusion on energy transition and do a comparative study of different regions with the purpose of benefiting from experiences of each other. To this end, two blocks of countries i.e., G20 countries and South Asian countries were sampled, and annual based data from 2001 to 2022 of all variables incorporated in this study were collected. The objective of this study promoted the use of panel data and panel research design.

Panel data series face econometric problem of non-stationarity due to its time series component. Therefore, the problem of non-stationarity was examined. Cross sectional dependence test was conducted as first-generation unit root test does not produce reliable results in presence of cross-sectional dependence and the results indicate the presence of cross-sectional dependence, therefore, second generation unit root test was used to examine the non-stationarity problem. The existence of cross-sectional dependence also makes traditional panel data estimation technique inconsistent and inefficient, therefore, feasible generalized least square method was used to estimate the model of this study.

The outcome of this study also demonstrates a positive and significant effect of technological diffusion on energy transition in G20 countries and South Asia. Technological diffusion, measured by human capital, enables the people to adopt renewable technologies and increases energy use efficiency. The findings of this study demonstrate that inverted U-shaped relationship, inferred from EKC Hypothesis, exists between energy transition and income per capita for both G20 countries and South Asia. At Initial stage of growth, an increase in income obstructs energy transition due to people disregard for environment and more reliance on fossil fuels. After certain point of high income, further increase in income positively affects energy transition as countries and their people get the affordability to import and produce renewable energy technology and concerns regarding environment get arise in these countries at high level of growth and development. This study indicates the positive influence of globalization on energy transition in both blocks of countries. Plausible reasons of deriving energy transition by globalization are the transfer of renewable energy technologies, and dissemination of knowledge regarding use of renewable energy.

This study also provides, based on its outcome, policy prescriptions for accelerating energy transition: the study suggests that policies should be directed towards increasing stock of human capital as human capital plays significant role in technological diffusion and technological diffusion accelerates energy transition. The findings of the study show that U-shaped relationship exists for energy transition-Income nexus, therefore, policy makers of these countries are suggested to formulate polices that cause increase in income per capita so that process of energy transition get accelerated. The study also advises policy makers to promote integration and trade among countries for transfer of renewable energy technologies and to learn best practice of energy conservation from others as the study's outcome shows positive effect of globalization on energy transition. The accelerating effect of governance on energy transition, as found by this study, is profound for governments of these countries and they are suggested to keep maintain and keep improve their governance especially the governing of resource allocating for use renewable energy and effective implementation of policies for energy transition.

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